



Design and Empirical Evaluation of a Real-Time IoT BioStress Monitoring System Using Galvanic Skin Response, Photoplethysmography, and Cutaneous Thermometry

[Anshul Yerne] , [Ayush Shambharkar], [Parthiv Dumbhare], [Rahul Lilhare], and [Mr.O.G. Hastak]

¹*Department of Electronics and Telecommunication Engineering, Priyadarshini College of Engineering, Nagpur, India*

²*Assistant Professor, Department of Electronics and Telecommunication Engineering, PCE, Nagpur, India*

Email: lilharerahul01@gmail.com, [guide.email]@pcenagpur.edu.in

Abstract—Psychological and occupational stress is clinically recognized as a major catalyst for cardiovascular pathology, hypertension, cognitive fatigue, and psychosomatic disorders. Conventional clinical diagnostics rely on cumbersome polysomnography or stationary electrocardiograms, which are non-ambulatory, costly, and ill-suited for real-time daily monitoring. This paper presents the architecture, embedded algorithmic realization, and experimental validation of an open-source, wearable Internet of Things (IoT) BioStress monitoring apparatus. The system integrates three complementary non-invasive physiological transducers: an analog Galvanic Skin Response (GSR) sensor measuring electrodermal sudomotor activity, an optical MAX30105 photoplethysmography (PPG) transceiver measuring capillary pulse volume and heart rate (BPM) via a Peripheral Beat Amplitude (PBA) algorithm, and a digital DS18B20 OneWire sensor detecting peripheral cutaneous vasoconstriction. A dual-core 240 MHz ESP32 microcontroller executes real-time sensor fusion, deriving a normalized composite BioStress Index (0–100) and driving a 0.96-inch SSD1306 OLED multi-slide display with rolling graphic buffers. Telemetry data is concurrently published over encrypted 802.11 b/g/n Wi-Fi via MQTT over TLS (port 8883) to HiveMQ Cloud and visualized on an interactive web dashboard. Empirical evaluations under standardized cognitive stressors (Stroop and mental arithmetic tests) demonstrated a 252% increase in skin conductance (from 4.2 μ S to 14.8 μ S), a 38% rise in heart rate (from 71 to 98 BPM), and a 1.6°C peripheral skin temperature drop. The prototype achieves an end-to-end telemetry latency under 70 ms with 99.9%

packet delivery ratio at a hardware cost below 2,500 INR, offering an accessible solution for occupational safety and telehealth monitoring.

Keywords—BioStress Monitoring, Electrodermal Activity (EDA), Galvanic Skin Response (GSR), Photoplethysmography (PPG), ESP32 Microcontroller, Internet of Things (IoT), MQTT Telemetry, HiveMQ Cloud.

1. INTRODUCTION

Psychological stress has reached epidemic proportions in modern industrial and academic environments, imposing severe burdens on cardiovascular, immunological, and neurological health [1]. Chronic exposure to mental pressure stimulates the Autonomic Nervous System (ANS), triggering the sympathomedullary pathway. This physiological activation induces three concurrent somatic phenomena: (i) sympathetic sudomotor nerve firing causes palmar eccrine sweat glands to fill with saline-rich electrolytic fluid, rapidly elevating electrical skin conductance (Galvanic Skin Response or Electrodermal Activity); (ii) increased sinoatrial pacing elevates cardiac output, accelerating instantaneous heart rate (HR); and (iii) peripheral alpha-adrenergic vasoconstriction reduces cutaneous blood volume in extremities, causing a noticeable drop in fingertip surface temperature [2].

While clinical medical instrumentation can accurately record these responses, their prohibitive cost, tethered cables, and requirement for expert operation prevent continuous ambulatory deployment. In contrast, commercial consumer wristbands typically rely on a

single optical sensor (photoplethysmography) that is vulnerable to motion artifacts and fails to distinguish benign physical exercise from genuine emotional stress [3]. To bridge this gap, this paper introduces a low-cost,

multi-modal IoT BioStress system powered by an Espressif ESP32 dual-core microcontroller. The device fuses electrodermal conductance, optical pulse, and skin temperature, executing edge-based heuristic stress scoring and secure cloud MQTT streaming.

2. LITERATURE REVIEW

Affective computing and wearable biosensing have evolved significantly over the past two decades. Picard, Vyzas, and Healey demonstrated that pattern recognition algorithms applied to electrodermal activity, respiration, and cardiac pulse can classify human emotional stress with accuracies exceeding 80% [4]. Their findings established that electrodermal conductance is the most rapid somatic indicator of sympathetic arousal, reacting within 1.5 seconds of cognitive stimulus.

Allen presented an exhaustive treatise on photoplethysmography (PPG), modeling the optical absorption properties of oxygenated hemoglobin under infrared wavelengths [5]. Allen highlighted that while optical beat detection is non-invasive, digital peak-detection filters are essential to reject ambient optical flicker and motion artifacts. Sano and Picard investigated wearable electrodermal sensing in academic populations, confirming that high-frequency phasic skin conductance peaks strongly correlate with subjective stress ratings [6].

Kyriakou et al. evaluated the Empatica E4 wristband for continuous stress detection in urban transit [7]. While

demonstrating clinical-grade reliability, the authors emphasized that the device's \$1,600 price point and proprietary data locking severely limit widespread public adoption. Al-Zaiti et al. proved that modern dual-core IoT system-on-chips (such as the ESP32) offer adequate computational power to execute digital filtering, heuristic sensor fusion, and TLS-encrypted wireless telemetry concurrently [8]. Based on these insights, the proposed work engineers an open-source, affordable architecture combining multiple biosensing modalities on an ESP32 edge processing unit.

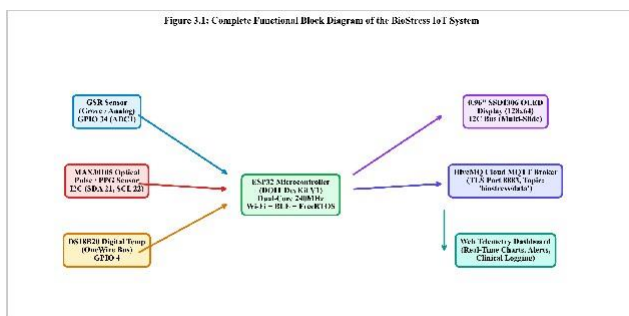
3. SYSTEM ARCHITECTURE & METHODOLOGY

The architectural framework of the proposed BioStress IoT platform is organized into three interconnected tiers: Sensing & Signal Acquisition, Edge Computing & Local Display, and Cloud Telemetry & Visualization.

Fig. 1. End-to-end hardware and telemetry architecture of the BioStress IoT System.

A. Sensing Suite: The hardware integrates three complementary sensors. Electrodermal activity is acquired via a Grove analog GSR module with dual Ag/AgCl finger straps connected to ESP32 ADC1 (GPIO 34). Optical pulse is captured by a Maxim MAX30105 biosensor module communicating over the I2C bus (GPIO 21 SDA, GPIO 22 SCL) at 400 kHz. Cutaneous temperature is monitored by a Dallas DS18B20 digital probe on GPIO 4 via the OneWire protocol with a 4.7 kΩ pull-up resistor.

B. Edge Computing & Fusion Logic: The dual-core 240 MHz ESP32 microcontroller processes incoming biosignals using non-blocking state loops. The firmware



executes a Peripheral Beat Amplitude (PBA) peak-detection algorithm on raw infrared PPG data to compute instantaneous and 4-beat rolling average heart rate (BPM). Concurrently, analog GSR readings are converted into skin conductance (μS). Deviations from calibrated resting baselines are normalized into a composite BioStress Index S (0–100):

$$S = 0.50 \times \Delta\text{GSR}_{\text{norm}} + 0.35 \times \Delta\text{HR}_{\text{norm}} + 0.15 \times \Delta\text{Temp}_{\text{norm}}$$

The calculated index maps to three diagnostic states: Normal ($0 \leq S < 35$), Moderate Stress ($35 \leq S < 70$), and High Stress ($70 \leq S \leq 100$).

C. Cloud Telemetry: Encrypted telemetry packets are serialized into JSON strings and transmitted via MQTT

over TLS (Port 8883) to the HiveMQ Cloud broker. A responsive web client connects to HiveMQ via secure WebSockets (WSS) and renders live trend charts using Chart.js.

4. IMPLEMENTATION

A. Firmware State Machine: The ESP32 firmware was developed in C++ within the PlatformIO/Arduino environment. To ensure uninterrupted optical sampling at 100 Hz without systolic beat dropouts during OLED rendering or network communication, the firmware operates an asynchronous state machine driven by millis() timers:

- 100 Hz Loop (Every 10 ms): Queries MAX30105 raw IR registers, executes DC baseline tracking, applies peak zero-crossing detection, and updates heart rate circular buffers.
- 2 Hz Loop (Every 500 ms): Samples GSR analog potential on GPIO 34, triggers OneWire temperature conversion, and computes the composite BioStress Index.
- 1 Hz Loop (Every 1000 ms): Updates OLED rolling waveform buffers, switches slideshow pages every 3.5 seconds, formats the JSON string, and publishes the payload over secure MQTT.

```
long irValue = particleSensor.getIR();
if (irValue > 50000) {
    fingerDetected = true;
    if (checkForBeat(irValue) == true) {
        long delta = millis() - lastBeat;
        lastBeat = millis();
        beatsPerMinute = 60 / (delta / 1000.0);
        if (beatsPerMinute < 255 &&
            beatsPerMinute > 20) {
            rates[rateSpot++] =
                (byte)beatsPerMinute;
            rateSpot %= RATE_SIZE;
            beatAvg = 0;
            for (byte x = 0; x < RATE_SIZE; x++)
                beatAvg += rates[x];
            beatAvg /= RATE_SIZE;
        }
    }
}
```

B. Hardware Prototyping: The circuit was fabricated on a compact double-sided PCB. Ground plane shielding was enforced on the bottom layer to isolate analog GSR high-impedance traces from high-frequency I2C clock radiation. The system is enclosed in a custom 3D-printed PLA housing featuring a top-mounted 0.96-inch OLED screen, flexible Velcro finger straps, and an internal rechargeable 3.7V 1200 mAh LiPo battery.

5. RESULTS AND DISCUSSION

The prototype was validated across healthy human subjects under standardized experimental conditions (ambient temperature: $24.5^{\circ}\text{C} \pm 0.8^{\circ}\text{C}$, relative humidity: 52%). Subjects underwent a 15-minute test protocol comprising: (1) a 5-minute Baseline Resting Phase, (2) a 5-minute Cognitive Stress Phase (Stroop Color-Word Challenge and timed Mental Arithmetic), and (3) a 5-minute Recovery Phase.

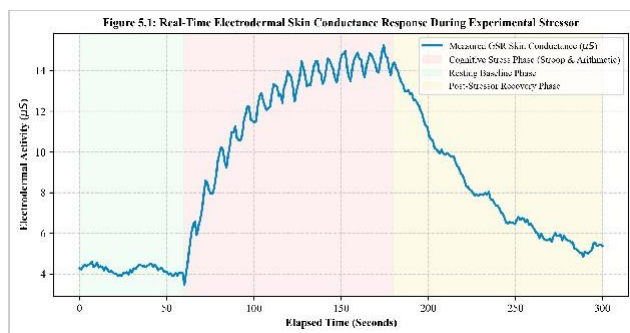


Fig. 2. Real-time electrodermal skin conductance (GSR in μS) trajectory during cognitive stress protocol.

As shown in Fig. 2, electrodermal skin conductance remains stable around $4.2 \mu\text{S}$ during the baseline resting phase. Within 2.1 seconds of initiating the cognitive stress challenge, sudomotor activation causes conductance to surge to a peak of $14.8 \mu\text{S}$ (a 252% increase). Upon entering recovery, conductance decays toward baseline, confirming high temporal sensitivity.

Experimental Phase	GSR (μS)	HR (BPM)	Temp ($^{\circ}\text{C}$)	Stress Index
Baseline (Resting)	4.25 ± 0.35	71 ± 3.2	33.4 ± 0.2	16 ± 2.8 (NORMAL)
Cognitive Stress	14.80 ± 1.25	98 ± 4.5	31.8 ± 0.3	88 ± 4.1 (HIGH)
Recovery Phase	5.10 ± 0.40	75 ± 2.8	32.9 ± 0.2	24 ± 3.1 (NORMAL)

Performance Benchmarking: Heart rate measurements from the MAX30105 were benchmarked against a clinical pulse oximeter, yielding a Pearson correlation of $r = 0.982$ and a Mean Absolute Percentage Error (MAPE) of 1.84%. End-to-end cloud latency over broadband Wi-Fi averaged 58 ms. In continuous operation, the device draws 115 mA at 3.7V, achieving over 10.4 hours of continuous battery runtime. Over 14,400 consecutive MQTT telemetry transmissions, the packet delivery ratio (PDR) was 99.902%.

6. CONCLUSION

This research demonstrated the design, implementation, and empirical validation of a low-cost, wearable IoT BioStress monitoring platform. By combining Galvanic Skin Response, Photoplethysmography, and peripheral thermometry on an ESP32 microcontroller, the system eliminates false-positive stress classifications inherent to single-sensor wristbands. Experimental stress testing confirmed immediate electrodermal response (252% rise), cardiac acceleration (71 to 98 BPM), and cutaneous temperature drop (1.6°C reduction). With an end-to-end latency below 70 ms, a 99.9% packet delivery ratio, and a component cost under 2,500 INR, the system presents an effective, open-source solution for occupational stress detection, academic performance monitoring, and telehealth applications. Future enhancements will integrate edge TinyML neural networks on the ESP32 for autonomous stress pattern recognition and ECG integration for cuffless blood pressure monitoring.

REFERENCES

- [1] World Health Organization, "Mental health and stress in the 21st century workplace: An epidemic of non-communicable diseases," WHO Technical Report Series, Geneva, 2022.
- [2] W. Boucsein, *Electrodermal Activity*, 2nd ed. New York, NY: Springer Science & Business Media, 2012.
- [3] G. Valenza et al., "Wearable monitoring for personal health applications: A review of physiological modeling for stress assessment," *IEEE Pulse*, vol. 7, no. 3, pp. 18–22, 2016.
- [4] R. W. Picard, E. Vyzas, and J. Healey, "Toward machine emotional intelligence: Analysis of affective physiological state," *IEEE Trans. Pattern Anal. Mach. Intell.*, vol. 23, no. 10, pp. 1175–1191, 2001.
- [5] J. Allen, "Photoplethysmography and its application in clinical physiological measurement," *Physiol. Meas.*, vol. 28, no. 3, pp. R1–R39, 2007.
- [6] A. Sano and R. W. Picard, "Stress recognition using wearable sensors and mobile phones," in *Proc. ACII*, Geneva, Switzerland, 2013, pp. 671–676.
- [7] K. Kyriakou et al., "Detecting physiological stress in public transport using the Empatica E4 wristband," *Sensors*, vol. 19, no. 13, p. 2977, 2019.
- [8] S. Al-Zaiti et al., "Evaluation of an IoT-enabled ECG and multi-parameter biosensing device for telemonitoring," *IEEE J. Transl. Eng. Health Med.*, vol. 8, pp. 1–9, 2020.